Late Paleozoic to Triassic arc magmatism north of the Sverdrup Basin in the Canadian Arctic: Evidence from detrital zircon U-Pb geochronology

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ABSTRACT

Paleozoic and Mesozoic tectonic reconstructions of the Arctic regions have been a subject of debate in recent years. The Permian emergence of a landmass north of the Sverdrup Basin in the Canadian Arctic led to the shedding of northerly derived detritus, an event that followed volcanism and basin inversion pulses that began in the late Pennsylvanian. However, the mechanisms for these events and the Paleozoic to Mesozoic paleogeography of this region remain controversial.

New detrital zircon U-Pb geochronology results from Permian to Lower Triassic strata from northern Axel Heiberg and Ellesmere islands constrain the magmatic events within this northern landmass and its implications for the tectonic regime of the Sverdrup Basin and adjacent domains. Permian to lowermost Triassic strata along the northern margin of the Sverdrup Basin contain zircons derived from Silurian to Devonian rocks (420–350 Ma), Timanian-aged basement (700–500 Ma), and a Permian syndepositional source (300–250 Ma). Coeval strata in the southern margin are dominated by zircons formed during the Taconic, Scandian, and post-Scandian phases of the Appalachian and Caledonian orogenies, respectively (480–400 Ma).

The detrital zircon signatures of the analyzed strata on the northern margin of the Sverdrup Basin record continuous magmatism within the northern landmass from latest Carboniferous (ca. 300 Ma) to at least earliest Triassic (ca. 250 Ma) time. These results are indicative of ongoing subduction and development of a magmatic arc off the northern margin of Laurentia, with the Sverdrup Basin potentially located in the backarc region of a proto-Pacific convergent margin involving parts of Arctic Alaska, Chukotka, and the Chukchi Shelf. The hypothesized onset of subduction in latest Carboniferous time and closure of this backarc basin in the latest Permian to earliest Triassic provides an explanation for the shift in stress regimes in the Sverdrup Basin that led to basin inversion and volcanism episodes. Therefore, the data presented here supports a backarc to retroarc setting for the Sverdrup Basin and the possibility of a convergent margin regime for the northern edge of Laurentia during the late Paleozoic to Triassic, contrasting with the generally accepted rift and passive margin settings.

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INTRODUCTION

Recent detrital zircon studies in the Arctic regions have shed light on sediment provenance, paleodrainage systems, and terrane positions throughout the Paleozoic and Mesozoic (e.g., Anfinson et al., 2012a, 2012b, 2016; Harrison, 1995; Beauchamp et al., 2001; Embry, 1993, 2009). Similarly, another hypothetical landmass comprising an amalgamation of Arctic terranes was proposed by Zonenshain (1990), recognized as Arctica. In this study, we use detrital zircon U-Pb geochronology on Carboniferous to Triassic strata along the northern and southern margins of these terranes to the continental margins, aiding to unravel the geological histories of the different circum-Arctic domains.

The late Paleozoic evolution of the Sverdrup Basin in the Canadian Arctic is marked by poorly understood basin inversion events and volcanism, coupled with the onset of northerly derived siliciclastic sediments; all of these potentially related to the emergence of an enigmatic landmass, termed “Crockerland” by Embry (1993), adjacent to the northern margin of the basin during the Middle Permian (Embry, 1993; Harrison, 1995; Beauchamp et al., 2001; Embry and Beauchamp, 2008). The term “Crockerland” is herein used to refer to the hypothesized landmass that provided a source of northwesterly derived sediments to the Sverdrup Basin from the Middle Permian to the Jurassic, nowadays located within the continental shelf of the Chukchi Borderlands (Embry, 1993, 2009). Similarly, another hypothetical landmass comprising an amalgamation of Arctic terranes was proposed by Zonenshain (1990), recognized as Arctica. In this study, we use detrital zircon U-Pb geochronology on Carboniferous to Triassic strata along the northern and southern margins...
of the Sverdrup Basin (Fig. 1) to investigate their sediment sources and their links to the emergence of Crockerland in the Middle Permian, with the purpose of constraining the tectonic setting of the Sverdrup Basin and adjacent domains during the late Paleozoic to Mesozoic.

Detrital zircon U-Pb geochronology studies in the Canadian Arctic and Arctic Alaska have shed light into the crustal affinity of Crockerland and the provenance of sub-Carboniferous and Mesozoic terrigenous sediments (Miller et al., 2006, 2013; Beranek et al., 2010; Lemieux et al., 2011; Omma et al., 2011; Anfinson et al., 2012a, 2012b, 2013, 2016; Midwinter et al., 2016). Anfinson et al. (2012a) suggested a Timanian and Caledonian origin for Crockerland, based on the predominance of 700–500 Ma and 450–365 Ma detrital zircon sub-populations found in northerly derived Devonian strata in the Franklinian Basin, the Neoproterozoic to Devonian predecessor of the Sverdrup Basin. Anfinson et al. (2012b) determined that the 450–365 Ma magmatism on Crockerland had a juvenile signature, which they interpreted as evidence of ongoing subduction beneath Crockerland prior to its accretion to the Laurentian margin in the Late Devonian. The emergence of Crockerland in the Middle Permian remains unexplained and its potential linkage to the inversion of rift structures in the Sverdrup Basin not established. These basin inversion events led to the partial exhumation of rift-related depocenters and generation of several unconformities, two of which are angular, beneath Middle Permian and uppermost Permian–Lower Triassic strata. The pre-Middle Permian basin inversion events are collectively termed the “Melvillian Disturbance” (Thorsteinsson and Tozer, 1970; Harrison, 1995; Beauchamp et al., 2001) with structural and stratigraphic evidence of compressional deformation observed all along the southern and northern margins of the Sverdrup Basin. Evidence for the unnamed pre-latest Permian–Early Triassic event is essentially from northern Axel Heiberg Island (Mayr et al., 2002), and possibly from the Tanquary Structural High on central Ellesmere Island (Maurel, 1989; Trettin and Mayr, 1997).

The U-Pb age data set presented here is used to analyze variations in sediment sources and pathways across major Permian unconformities in the Sverdrup Basin, and to determine their relationship to the Pennsylvanian to Permian pulses of basin inversion, volcanism, and onset of northerly derived clastic sedimentation. These results contribute to...
unraveling the tectonic evolution of the Canadian Arctic and explore the timing of magmatism and its implications for the geodynamic significance of Crockerland during the late Paleozoic to earliest Mesozoic.

**GEOLOGICAL BACKGROUND**

The late Paleozoic history of the Canadian Arctic is characterized by sedimentation within a NE to SW elongated depocenter: the Sverdrup Basin (Fig. 1). This basin has been shown to have originated as a rift, presently spanning over an area of 300,000 km², preserving 13 km of Mississippian to Eocene strata disrupted by numerous deformation events and unconformities (Balkwill, 1978; Trettin, 1991; Embry and Beauchamp, 2008).

The Sverdrup Basin is the successor to the Franklinian Basin, which preserves a Neoproterozoic to Upper Devonian sedimentary record along the northern edge of Laurentia (Balkwill, 1978). By the Silurian, Pearya had collided against the northeastern portion of the Franklinian Basin, resulting in the development of the Clements-Markham Fold Belt and the deposition of flysch units as an overlap or a syn-collisional sequence (Trettin, 1987, 1998; Klaper, 1992; Hadlari et al., 2014; Beranek et al., 2015). Collision led to deepening of the northeastern portion of the basin, which was filled by northerly sourced flysch units of Silurian age found in northern Ellesmere Island (Beranek et al., 2015). By the Middle Devonian Crockerland approached the Franklinian Basin, as evidenced by renewed deepening and widespread northwesterly derived sedimentation throughout the basin (Trettin, 1998). Final accretion of Crockerland against the Laurentian margin led to the latest Devonian Ellesmerian Orogeny and the deposition of molasse sediments, which blanketed northern Laurentia and are preserved as the Devonian Clastic Wedge (Thorsteinsson and Tozer, 1957; Embry, 1988, 1991; Patchett et al., 2004).

The Ellesmerian Orogen experienced post-collisional collapse in the earliest Carboniferous, during which compressional structures were reactivated in an extensional regime (Harrison, 1995). This yet-to-be-understood shift in stress directions produced a depocenter in which syn-rift sedimentation dominated, representing the first tectonostratigraphic phase of the Sverdrup Basin (Embry and Beauchamp, 2008). This first phase recorded three major pulses of rifting, coinciding with the Viséan, Serpukhovian, and Bashkirian sequences (Fig. 2) associated with deposition of syn-rift clastic, carbonate, and evaporite sediments covering an increasingly broader area with each subsequent pulse (Embry and Beauchamp, 2008).

Post-rift quiescence and thermal subsidence prevailed during most of the Pennsylvanian and Permian, punctuated by at least three basin inversion episodes from the latest Carboniferous to the early Permian (Fig. 2), collectively recognized as the Melvillian Disturbance (Thorsteinsson and Tozer, 1970; Stephenson et al., 1987; Beauchamp et al., 2001). The second tectonostratigraphic phase is characterized by these pulses of renewed tectonic activity with synchronous basaltic magmatism and deposition of volcaniclastic material, and followed by a marine transgression (Harrison, 1995; Beauchamp et al., 2001; Embry and Beauchamp, 2008). Growth faulting along reactivated Ellesmerian structures in the Franklinian Basement, broad scale folding, local thrust faulting and regional uplift, are all products of what Harrison (1995) interpreted to be a single southeast-directed compressional episode. Multiple deformation events from the Ghelbian (late Late Pennsylvanian) to the Changhsingian (late Late Permian) were later recognized by Beauchamp et al. (2001) and Beauchamp (2015), some involving half-graben inversion and normal faulting, suggesting more complex, possibly transpressive to transtensive, stress conditions during these pulses (Fig. 2). As a result of these deformation episodes, passive thermal subsidence of the basin during the Carboniferous and Permian was overwhelmed by short episodes of fault-controlled subsidence, leading to the creation of numerous local depocenters and regional unconformities along both northern and southern basin margins (Stephenson et al., 1987; Beauchamp et al., 2001; Embry and Beauchamp, 2008).

The first major unconformity resulting from these episodes is the sub-Roadian (sub-early Middle Permian) unconformity, recognized along both basin margins and in the subsurface (Thorsteinsson, 1974; Beauchamp et al., 2001). Overlying this unconformity on the northern margin is a variably thick, northerly derived clastic wedge including the Assistance and Trolfdi Fiord formations, recording the first significant clastic input from Crockerland (Thorsteinsson, 1974; Embry, 1993, 2009; Beauchamp et al., 2009; Beauchamp, 2015). Similar Middle Permian deformation and a transition from carbonate platform to siliciclastic sedimentation is also documented in the northern Barents Sea and Svalbard within the Tempelfjorden Group (Worsley, 2008), suggesting that these processes were regional in extent and not restricted to the Sverdrup Basin.

The second major unconformity is the sub-Changhsingian (sub-late Permian) angular unconformity (Fig. 2). On northern Axel Heiberg Island, folded upper Paleozoic strata are truncated and overlain by homoclinal shales and sandstones of the uppermost Permian to Lower Triassic Blind Fiord Formation (Fig. 3) (May et al., 2002). On the southern margin of the Sverdrup Basin, lowermost Triassic strata of the Bjoern Formation record cratonic uplift that was synchronous with deformation events and uplifts on the northern margin (Embry and Beauchamp, 2008).

Crockerland, which remained exposed throughout the Triassic to Middle Jurassic, underwent riftting and ultimately separated from the Laurentian margin by the Cretaceous, leading to the opening of the Amerasia Basin (Embry, 1993, 2009; Hadlari et al., 2016). Due to this event, the landmass referred to as Crockerland lies buried beneath post-Jurassic strata, along with other terranes included within Arctic Alaska–Chukotka Microplate (Embry, 1993, 2009; Pease, 2011). Tectonic movements between Greenland and North America during the Paleocene caused the Eurekan Orogeny, which deformed and uplifted the Sverdrup Basin and led to its demise as a sedimentary basin (Embry and Beauchamp, 2008).

Detrital zircon studies in the Canadian Arctic Islands have focused on Neoproterozoic to uppermost Devonian strata of the Franklinian Basin (McNicoll et al., 1995; Anfinson et al., 2012a, 2012b, 2013; Hadlari et al., 2014; Beranek et al., 2015), Neoproterozoic to Silurian units on the Pearya terrane (Hadlari et al., 2014; Malone et al., 2014) and Carboniferous to Permian syn-rift formations of the Sverdrup Basin (Malone, 2012) and its Mesozoic succession (Miller et al., 2006; Omma et al., 2011; Rohr et al., 2010; Anfinson et al., 2016; Midwinter et al., 2016). Related detrital zircon studies that help constrain the sediment sources and tectonic evolution of the rocks in the Arctic realm were conducted in northernmost Laurentia and Greenland (Kirkland et al., 2009; Beranek et al., 2010; Lemieux et al., 2011; Hadlari et al., 2012) Arctic Alaska (Miller et al., 2006; Amato et al., 2009; Strauss et al., 2013; Gottlieb et al., 2014; Till et al., 2014), and the Barents Sea (Pettersson et al., 2009, 2010; Rue and Andresen, 2014; Klausen et al., 2017). The Russian margin has also been the subject of numerous detrital zircon studies. Franz Josef Land, the peri-Siberian islands, Novaya Zemlya, Taimyr Peninsula, the Verkhoyanski Margin, Chukotka, and the Chukchi Shelf have been extensively studied using detrital zircon geochronology in recent years (Miller et al., 2006, 2010; Lorenz et al., 2008, 2013; Pease and Scott, 2009; Tuchkova et al., 2014; Soloviev and Miller, 2014; Ershova et al., 2015a, 2015b, 2015c, 2016, 2017; Amato et al., 2015; Pease et al., 2015; Soloviev et al., 2015; Brumley et al., 2015; O’Brien et al., 2016). However, despite the increasing number of detrital zircon studies in the Arctic realm, mostly focusing on the Mesozoic and Devonian, the Carboniferous to Permian paleogeography of the northern Laurentian margin remains a knowledge gap crucial for understanding any subsequent plate configurations.
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Figure 2. Upper Paleozoic to Lower Triassic stratigraphy and tectonic regime of the Sverdrup Basin (adapted from Embry and Beauchamp, 2008). Detrital zircon sample position indicated with the black arrowheads. Deformation events and proposed strain ellipsoids and orientations in map view for both basin margins from field and seismic data (Harrison, 1995; Beauchamp et al., 2001; Beauchamp, 2015). Deformation in the basin center has not been studied due to the continuous record and lithological homogeneity of the units and the associated distinction difficulties between formations in the field. GBC—Great Bear Cape; LCM—Lower Canyon Fiord member; MCM—Middle Canyon Fiord member; TF—Trold Fiord Formation; UCM—Upper Canyon Fiord member; ULV—Unnamed lower volcanics (Morris, 2013).
Figure 3. Simplified geological map of northern Axel Heiberg Island (modified from Mayr et al., 2002). The red stars mark the field localities referred to in this study, sample locations indicated.
ANALYTICAL METHODS

Sample Preparation

A total of 19 samples were collected during several field seasons, catalogued and archived at the Geological Survey of Canada (GSC) in Calgary, Alberta. The samples were processed to recover detrital zircons following procedures outlined in Matthews and Guest (2016). Samples were crushed using a Bico™ Chipmunk jaw crusher, and pulverized using a Bico™ disk mill. Large samples were processed using a MD Gemini water table to separate dense minerals (e.g., zircon and apatite) from less-dense minerals (e.g., quartz and feldspar). Smaller samples were rinsed with water in a beaker to remove the clay fraction. The dense mineral fraction was further concentrated using methylene iodide and the resulting dense fraction underwent magnetic separation using a Frantz™ isodynamic separator. A random population of zircons was cast in epoxy pucks, ground to expose the interior of the grains, and polished using silicon carbide and diamond polishing films. All samples were cleaned in diluted HNO₃ prior to analysis to reduce surface Pb contamination.

U-Pb Geochronology

U-Pb isotopic measurements were obtained using laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) techniques at the Centre for Pure and Applied Tectonics and Thermochronology (CPATT) at the University of Calgary following the methodology described in Matthews and Guest (2016). Instrument settings are listed in the Table of Acquisition Parameters in the Data Repository. Zircons were ablated using an ASI Resochron™ excimer laser ablation system in the mount to minimize grain size bias. The well-characterized FC-1 zircon (Paces and Miller, 1993) was used as the calibration reference material and six validation reference materials, the 91500 zircon and 1242 (Mortensen and Card, 1993), NIST SRM 610 Glass (Stern and Amelin, 2003), FCT (Kuiper et al., 2008), and TRD (Ganerød et al., 2011) were ablated every 20 unknowns in order to assess the accuracy and uncertainty of the data. Isotopic signal intensities were measured using an Agilent 7700 quadrupole ICP-MS, and the data reduction handled in Iolite v. 2.5 (Paton et al., 2010). Subsequent data filtering and uncertainty propagation was carried out in Excel using a custom VBA macro (ARS4.0) and the Isoplot plug-in of Ludwig (2012).

Measurements were filtered using the probability of fit parameter from the concordia age algorithm in Isoplot (Ludwig, 1998). Measurements with <1% probability of fit were omitted from the data set. Probability density plots were constructed from Best Ages calculated using both random and systematic components of uncertainty with the cutoff between 206Pb/238U and 207Pb/206Pb dates at 1550 Ma, following recommendations by Spencer et al. (2016).

SAMPLES AND RESULTS

The 19 samples analyzed in this study are displayed as 11 samples and 2 composite samples, combined after analysis. The samples are labeled as SvB-# (Table 1).

Pennsylvanian (Northern Margin)

Sample SvB-01 was collected at River Section, northern Axel Heiberg Island (Fig. 3), from red-weathering fluvial to marginal marine sandstones (Fig. 4A) within the upper Nansen Formation, just beneath an unnamed intra-Nansen basalt (Figs. 2 and 4A). Fusulinaceans recovered immediately below and above this basalt suggest a Gzhelian (late Pennsylvanian) age for both the volcanic rocks and the sandstone unit (Fig. 2), (D. Baranova, personal commun., 2016).

Sample SvB-01 yielded 257 concordant dates dominated by 450–400 Ma, 1050–1000 Ma, and 1650–1600 Ma sub-populations (Fig. 5). These groupings do not form isolated peaks but are part of two larger

TABLE 1. DETAIL OF THE SAMPLES ANALYZED FOR DETRITAL ZIRCON GEOCHRONOLOGY IN THIS STUDY

<table>
<thead>
<tr>
<th>DZ sample #</th>
<th>Sample #</th>
<th>Sequence</th>
<th>Coordinates (WGS84)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>SvB-1</td>
<td>DA-19</td>
<td>Gzhelian</td>
<td>80.875605,–94.178196</td>
<td>River Section (Northern Axel Heiberg Island)</td>
</tr>
<tr>
<td>SvB-2</td>
<td>DA-20</td>
<td>Asselian</td>
<td>80.817048,–94.001547</td>
<td>Folds Creek (Northern Axel Heiberg Island)</td>
</tr>
<tr>
<td>SvB-3</td>
<td>DA-21</td>
<td>Sakmarian</td>
<td>80.817117,–93.999253</td>
<td></td>
</tr>
<tr>
<td>SvB-4</td>
<td>1-9-1</td>
<td>Kungurian</td>
<td>81.038514,–81.704574</td>
<td></td>
</tr>
<tr>
<td>SvB-5</td>
<td>1-16-1</td>
<td></td>
<td>81.038571,–81.707039</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-49-3</td>
<td></td>
<td>81.038717,–81.704713</td>
<td></td>
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<td></td>
<td>1-91-7</td>
<td></td>
<td>81.038715,–81.707574</td>
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</tr>
<tr>
<td></td>
<td>1-93-1</td>
<td></td>
<td>81.038805,–81.708488</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-99-1</td>
<td></td>
<td>81.038637,–81.708484</td>
<td></td>
</tr>
<tr>
<td>SvB-6</td>
<td>DA-23</td>
<td>Guadalupian-Lopingian</td>
<td>80.816934,–94.013604</td>
<td>Folds Creek (Northern Axel Heiberg Island)</td>
</tr>
<tr>
<td>SvB-7</td>
<td>DA-22</td>
<td>Roadian</td>
<td>80.754892,–93.383664</td>
<td>Bukken River (Northern Axel Heiberg Island)</td>
</tr>
<tr>
<td>SvB-8</td>
<td>96-04/97-25</td>
<td>Guadalupian</td>
<td>80.760375,–93.349407</td>
<td>Bukken River (Northern Axel Heiberg Island)</td>
</tr>
<tr>
<td>SvB-9</td>
<td>DA-24</td>
<td>Guadalupian-Lopingian</td>
<td>80.998341,–92.065983</td>
<td>Nice Valley (Northern Axel Heiberg Island)</td>
</tr>
<tr>
<td>SvB-10</td>
<td>DA-25</td>
<td>Lopingian</td>
<td>80.725273,–93.757603</td>
<td>Conglomerate Section (Northern Axel Heiberg Island)</td>
</tr>
<tr>
<td>SvB-11</td>
<td>C601095</td>
<td>Lopingian</td>
<td>80.494518,–94.515296</td>
<td>Griesbach Creek (Northern Axel Heiberg Island)</td>
</tr>
<tr>
<td>SvB-12</td>
<td>DA-26</td>
<td>Induan</td>
<td>80.816891,–94.013094</td>
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<tr>
<td>SvB-13</td>
<td>1997-26-01</td>
<td></td>
<td>80.816335,–94.016808</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1997-26-02</td>
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<td>80.816341,–94.016811</td>
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</tr>
<tr>
<td></td>
<td>1997-26-03</td>
<td></td>
<td>80.816344,–94.016816</td>
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</table>

GSA Data Repository Item 2018093, detrital zircon U-Pb LA-ICP-MS geochronology data, is available at http://www.geosociety.org/datarepository/2018, or on request from editing@geosociety.org.
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Figure 4 (on previous page). Field photographs of the sample locations and their stratigraphic relations (CPn—Carboniferous-Permian Nansen Formation; CPv—Carboniferous-Permian volcanics; Pgc—Permian Great Bear Cape Formation; PEs—Permian Esayoo Formation; PBs—Permian Sabine Bay Formation; PA—Permian Assistance Formation; PT—Permian Trolfd Fiord Formation; PL—Permian Lindström Formation; PTF—Permian-Triassic Blind Fiord Formation; TF—Triassic Blind Fiord Formation). Arrows indicate the location and sample number (Table 1). (A) Red sandstones interfingering with the Carboniferous–Permian volcanics at the River Section locality, northern Axel Heiberg Island. (B) Borup Fiord Pass section, the yellow square represents the area shown in detail in C. Note how the unconformity at the base of the Sabine Bay Formation cuts deeper stratigraphically toward the northeast (right). Ki—Cretaceous intrusion. (C) Detail of the unconformable contact between the Esayoo Formation and the Sabine Bay Formation on top. (D) The Permian-Triassic Blind Fiord Formation overlies folded strata of the Great Bear Cape Formation through an unconformable contact at the Folds Creek locality. ss—red weathering, bivalve-rich sandstone; c—boulder-sized chert conglomerate. (E) Detail of the red Roadian (lower Middle Permian) conglomerates at the Bukken River section in northern Axel Heiberg Island. rc—Red weathering conglomerate. (F) Bukken River section, northern Axel Heiberg Island. (G) Detail of the conglomerates above the Great Bear Cape Formation at the Conglomerate Section locality on northern Axel Heiberg Island. (H) Griesbach Creek section, where the Permian–Triassic Blind Fiord lies unconformably on an unnamed Permian unit (un—Maroon conglomerates and sandstones).

Figure 5. Probability density plots and histograms of Pennsylvanian to lower Permian strata of the northern margin of the basin, and lower to Middle Permian strata of the southern margin. n—number of accepted analyses; s—number of samples.
yielded 967 concordant dates, exhibiting a similar signature to that of the composite sample SvB-05 (Fig. 5). In total, composite sample SvB-05  
  
**Lower Permian (Northern Margin)**

Two Lower Permian samples were collected in the Folds Creek area on northern Axel Heiberg Island (Fig. 3). Sample SvB-02 is from a thin conglomerate bed that lies unconformably on the Nansen Formation and beneath the Sakmarian (Early Permian) Raanes Formation, a stratigraphic position that suggests a late Asselian (early Early Permian) or early Sakmarian age (Fig. 2). Sample SvB-03 is from a sandy conglomerate that rests unconformably on carbonate rocks of the Raanes Formation and beneath spiculitic chert of the Great Bear Cape Formation, a stratigraphic position indicative of a late Sakmarian to early Artinskian (middle Early Permian) age (Fig. 2).

Sample SvB-02 yielded 236 concordant measurements with prominent groupings between 450 and 400 Ma, 1100 and 1000 Ma, and 1700 and 1600 Ma. Sample SvB-03 yielded a total of 252 concordant dates with dominant sub-populations between 450 and 400 Ma, 650 and 550 Ma, 1200 and 950 Ma, 1450 and 1350 Ma, and 1750 and 1550 Ma. The three grains younger than the stratigraphically constrained age of the sample are considered to be a product of laboratory contamination or Pb loss.

**Lower Permian (Southern Margin)**

Sample SvB-04 was collected at Borup Fiord Pass (Figs. 1 and 2) from a shale unit that lies on top of the Kungurian (latest Early Permian) Esayoo basalt. In this section, Kungurian rocks unconformably overlie Artinskian (middle Early Permian) carbonate rocks of the Great Bear Cape Formation and are unconformably overlain by the Middle Permian Sabine Bay and Assistance formations (Figs. 4B and 4C). The Esayoo Volcanics at Borup Fiord Pass comprise 75 m of basalts that are overlain by 3 m of shale, recording the maximum flooding surface that followed extrusion of the lava (Morríis, 2013).

Sample SvB-04 yielded a total of 201 concordant dates, with two dominant detrital zircon sub-populations ranging from 450 to 400 Ma and from 2050 to 930 Ma, and two minor ones from 3250 to 2330 Ma and from 650 to 500 Ma. The relative abundance of these detrital zircon sub-populations is similar to Pennsylvanian to Lower Permian strata from the northern margin of the basin (SvB-01, SvB-02).

**Middle Permian (Southern Margin)**

A total of five samples consisting of white- to tan-colored Roadian (Middle Permian) sandstone were collected at the Borup Fiord Pass section (Fig. 1), where unfossiliferous strata with minor amounts of chert and carbonate rock fragments (Sabine Bay Formation) pass upward into increasingly fossiliferous calcareous sandstones (Assistance Formation). This succession rests upon the Esayoo Formation basalt and shale (Figs. 4A and 4B) in a low-angle angular unconformity, marking the culmination of the Early Permian deformation episodes in the southern margin collectively known as the Melvillian Disturbance (Thorsteinsson, 1974; Beauchamp et al., 2001). During the Roadian (early Middle Permian) the northern margin of the basin began receiving terrigenous clastic sediments from northern sources, first recorded as the correlative Assistance Formation on northern Axel Heiberg Island (Fig. 2).

Five Roadian samples from Borup Fiord Pass yielded nearly identical detrital zircon signatures and as such their results were combined into composite sample SvB-05 (Fig. 5). In total, composite sample SvB-05 yielded 967 concordant dates, exhibiting a similar signature to that of the Kungurian sample (SvB-04), with two dominant sub-populations from 450 to 400 Ma and 2100 to 900 Ma, and two smaller ones at 3200 to 2500 Ma and 700 to 500 Ma.

**Middle Permian (Northern Margin)**

Wordian and Capitanian sedimentation occurred at a time of maximum base level with deposition of the brachiopod-rich glauconitic sandstones of the Trolf Fiord Formation along both basin margins (Thorsteinsson, 1974; Embry and Beauchamp, 2008).

Sample SvB-06 was collected at the Folds Creek section from a conglomerate of uncertain age that lies between spiculitic chert of the Lower Permian Great Bear Cape Formation and a thin bivalve-rich red sandstone unit at the base of the Triassic Blind Fiord Formation. The conglomerate is locally more than 2 m thick but pinches out laterally over short distances (Fig. 4D). Pebble to cobble clasts in the conglomerate are composed almost exclusively of chert from the Great Bear Cape Formation. The conglomerate is likely the erosional product of Early to Middle Permian uplift and erosion, preserved within incised valleys and associated with the last pulse of the Melvillian Disturbance on northern Axel Heiberg Island (Fig. 2). A Late Permian age is less likely as it contains no clasts derived from the erosion of the Assistance or Trolf Fiord formations.

The 152 measurements from sample SvB-06 exhibit a dominant 700–350 Ma sub-population and less abundant 2000–900 Ma and 3300–2500 Ma sub-populations than older strata in the basin (Fig. 6). A single Cretaceous grain is regarded as either laboratory contamination, or to have suffered significant Pb loss based on the stratigraphic constraints on the sample.

Sample SvB-07 was collected from a thin, red-weathering chert pebble conglomerate at the Bukken Fiord section that lies between spiculitic chert of the Great Bear Cape Formation and maroon-weathering shale and siltstone of the Assistance Formation (Figs. 3 and 4E). The conglomerate forms a thin yet laterally extensive unit that is likely Roadian and is thus either of the same age or slightly younger than sample SvB-06 (Fig. 2).

Sample SvB-07 yielded 241 concordant dates and shows a prominent 300–260 Ma sub-population, with the mode at 270 Ma, accompanied by a 450–370 Ma sub-population and a 670–490 Ma sub-population (Fig. 6). Smaller sub-populations yield dates between 2000 and 900 Ma and 3500–2300 Ma.

Sample SvB-08 was collected from the Trolf Fiord Formation at the Bukken River section, where it lies above the Assistance Formation (Fig. 4F). At this section the Trolf Fiord Formation comprises bioturbated brachiopod-rich, greenish gray glauconitic sandstone of shallow marine origin. The Trolf Fiord Formation at Bukken River is either Wordian or Capitanian in age (Fig. 2).

Sample SvB-08 yielded 236 concordant dates that define a detrital zircon signature similar to that of SvB-07. Sample SvB-08 is dominated by a 700–360 Ma sub-population and contains a less prominent 2000–900 Ma and 3100–2700 Ma sub-population (Fig. 6). The Permian sub-population (300–260 Ma) described in sample SvB-07 is also present and centered at 265 Ma, although it is less abundant in sample SvB-08 than in SvB-07.

Sample SvB-09 was collected from the Trolf Fiord Formation in an area called Nice Valley (Fig. 3), where greenish-gray glauconitic sandstones lie with mild angular unconformity directly on top of the Great Bear Cape Formation. Another low-angle angular unconformity separates the Trolf Fiord Formation from the overlying Blind Fiord Formation, attesting for a latest Permian–earliest Triassic episode of uplift and erosion on northern Axel Heiberg Island (Fig. 2). The sandstones of the Trolf Fiord Formation contain abundant brachiopods, indicative of a Wordian or Capitanian age (Beauchamp et al., 2009).
Late Paleozoic to Triassic Arc magmatism north of the Sverdrup Basin

Figure 6. Probability density plots and histograms from the Middle to Upper Permian samples from northern Axel Heiberg Island analyzed in this study. n—number of accepted analyses; s—number of samples.
Sample SvB-09 yielded 242 concordant dates with a dominant sub-population yielding dates between 650 and 350 Ma, and smaller sub-populations from 295 to 250 Ma and 2100 to 800 Ma. Archean grains are scarce in the sample and appear distributed between 3000 and 2500 Ma.

### Upper Permian (Northern Margin)

The Upper Permian sedimentary record on northern Axel Heiberg Island is scarce due to erosion beneath the sub-Changhsingian unconformity (Mayr et al., 2002). Chert and sandstone rocks of the Degerböl and Trolid Fior formation are irregularly exposed in the area, but are locally absent or very thin in the north-central part of northern Axel Heiberg Island (Fig. 3). Maroon conglomeratic and sandstone bodies of limited lateral extent can be found on northern Axel Heiberg Island above the Great Bear Cape Formation and below the Blind Fiord Formation (Fig. 4D).

Sample SvB-10 was collected from a gray cobble conglomerate immediately beneath the sub-Changhsingian unconformity at the Conglomerate Section (Figs. 3 and 4G), where it sits on spiculitic chert of the Great Bear Cape Formation. The conglomerate interfingers with sandstone but pinches out laterally over short distances, suggesting it is filling a topographic low on an unconformity surface. These conglomerates are assumed here to be Late Permian in age based on the youngest dates present in its detrital zircon signature, with a 2σ maximum depositional age of 252.4 ± 3.3 Ma, based on six grains (Dickinson and Gehrels, 2009).

Sample SvB-10 yielded 276 concordant dates, dominated by a 400–340 Ma sub-population from 430 and 345 Ma (with a mode at 384 Ma) and 1950 and 900 Ma, and two minor sub-populations from 750 to 500 and 2850 to 2400 Ma (Fig. 7), similar to the upper Permian samples from the northern margin of the basin, though with fewer zircons of Permian age.

### Lower Triassic (Northern Margin)

The Triassic succession in the Sverdrup Basin begins with Bjorne Formation strata along the southern margin and Blind Fiord Formation strata along the northern margin (Embry and Beauchamp, 2008). At the Folds Creek locality on northern Axel Heiberg Island, these deposits overlie, in homoclinal structure, folded Pennsylvanian to Permian strata across the sub-Changhsingian unconformity (Fig. 4D) (Embry and Beauchamp, 2008). The Blind Fiord Formation comprises conglomerate, sandstone, and shale that were deposited in shallow to deep marine settings (Thorsteinsson, 1974; Embry, 1993; Embry and Beauchamp, 2008). A major deepening and widening event of the Sverdrup Basin and associated increase in sediment supply coming from northern sources are thus recorded in the Induan–Olenekian second-order sequence of the Sverdrup Basin (Fig. 2), (Embry and Beauchamp, 2008; Embry, 2009).

The Triassic samples, combined into composite sample SvB-13, were collected at the Folds Creek locality from sandstones at the top of the first of three late Induan third-order sequences (Fig. 4D) (Embry, 1988). Embry (2009) provided evidence that the abundant siliciclastic material in the Lower Triassic succession along the northern margin of the Sverdrup
Basin was derived from Crockerland to the north, and attest to a time when drainage systems were better integrated.

Composite sample SvB-13 yielded a total of 314 measurements, with few grains older than 800 Ma and dominated by the sub-populations between 295 and 250 Ma, 380 and 340 Ma, and 700 and 500 Ma (Fig. 7). The 700–500 Ma sub-population is less abundant than in the older samples, and the 295–250 and 400–350 Ma sub-populations are also in lesser abundance. The 480–400 Ma and 2000–900 Ma grains are scarce in the sample and widely distributed along these intervals.

DISCUSSION

Provenance Implications

Late Carboniferous to Early Permian Terrigenous Sediment Sources

The similarities between the detrital zircon signatures of upper Pennsylvanian to Lower Permian strata of the northern and southern margins of the Sverdrup Basin are indicative of shared sediment sources. Detrital zircon populations in these samples are similar to those from the Silurian (Pridoli) Danish River Formation on Ellesmere Island, both containing 2000–900 Ma sub-populations, with the modes at ca. 1750, 1420, and 1020 Ma, and from Devonian Clastic Wedge strata, containing a sub-population with a prominent ca. 2000 Ma mode (Fig. 8) (Anfinson et al., 2012a; Beranek et al., 2015). A recycled Silurian sedimentary source with minor contributions from recycled Devonian strata is also supported by the relatively small proportion of 400–350 Ma and 700–500 Ma grains in these samples, contrasting with their prominence in Devonian Clastic Wedge strata (Fig. 8) (Beranek et al., 2010; Anfinson et al., 2012a, 2012b). It is also noteworthy that sample SvB-01, despite being from a sandstone interfingered with basalts and volcaniclastic rocks, does not contain grains yielding dates near the known depositional age.

These results indicate that during the late Pennsylvanian to Early Permian sediments that accumulated along both the northern and southern margins of the Sverdrup Basin were either derived from recycling of the Danish River Formation and other Franklinian Basin strata, or from the same ultimate sources, that is the East Greenland Caledonides, Pearya, and the Laurentian Shield (Anfinson et al., 2012a; Hadlari et al., 2014; Beranek et al., 2015). On the northern margin, the sampled units exhibit petrological characteristics typical of proximal derivation, such as a red weathering color, a narrow lateral extent of the red sandstone within the volcanic units (sample SvB-01), cobble-sized clasts and limited areal extent of the units on top of the Nansen and Raanes formations (SvB-02 and SvB-03). On the southern margin, Middle Permian sediments were deposited unconformably on the maximum flooding surface of the underlying Kungurian (uppermost Lower Permian) sequence, filling local depocenters created by an episode of basin inversion with small drainage areas and local reworking of sediment (Harrison, 1995; Embry and Beauchamp, 2008; Morris, 2013). Hence, based on the detrital zircon signature, facies, and stratigraphy of upper Pennsylvanian to Lower Permian strata of both basin margins it is likely that reworking of older units, particularly of Silurian age, was the main source sediment for these small depocenters.

The absence of zircons yielding dates younger than 365 Ma in all of the upper Pennsylvanian and Lower Permian samples indicates that synsedimentary volcanism in the area did not yield a significant number of zircons or that these zircons were not incorporated into the sampled units.

Middle Permian to Early Triassic Terrigenous Sediment Sources

Roadian (early Middle Permian) sediments that overlie the Kungurian (latest Early Permian) shale at Borup Fiord Pass along the southern margin of the Sverdrup Basin show a similar detrital zircon signature to that of the Lower Permian sediments on both basin margins. The major difference between the Kungurian and Roadian sequences is the addition of a 1700–1600 Ma sub-population, which is not as prominent in the Kungurian sample as in the Roadian one (Fig. 8). Magmatic rocks of this age interval are found in Grenvillian-aged basement of the Scandinavian Caledonides and southern Greenland (Kerr et al., 1996; Bingen and Solli, 2009; Pettersson et al., 2009, 2010; Gasser and Andresen, 2013). The prominence of the 1700–1600 Ma zircon sub-population can therefore be explained by derivation from more distal sources, such as the Sveconorwegian Orogen in the East Greenland Caledonides, reworking of Cambrian strata from northern Greenland, and reworking of Devonian Clastic Wedge strata with abundant grains of this age interval (Fig. 8) (Kirkland et al., 2012a; Anfinson et al., 2012a). The distal source interpretation is consistent with the inferred tectonic setting: a quiescent, thermally subsiding basin in which marine sediments accumulated shortly after peneplanation of inverted grabens created during the Melvillian Disturbance (Harrison, 1995; Beauchamp et al., 2001; Embry and Beauchamp, 2008). However, some reworking of older strata is required to explain the small 700–500 Ma sub-population, which is present in the Roadian and Kungurian samples and proposed to have been originally derived from Timanian-aged basement in Crockerland and shed into the Franklinian Basin during the Devonian (Anfinson et al., 2012a).

In contrast, detrital zircon signatures from Middle Permian to Lower Triassic sediments on northern Axel Heiberg Island point to a different source region, with some shared sub-populations with Devonian Clastic Wedge strata. The 700–500 Ma and 450–370 Ma sub-populations, abundant in the Middle Permian to Lower Triassic samples, are also dominant in strata of the Devonian Clastic Wedge, and have previously been interpreted to characterize the signature of sediments derived from Crockerland in the Devonian (Beranek et al., 2010; Anfinson et al., 2012a). Franklinian

![Figure 8. Comparison of the probability density plots of Lower to Middle Permian strata of the southern margin of the basin analyzed in this study with other data sets. n—number of accepted analyses; S—number of samples.](https://example.com/image.png)
Basin sediments derived from Pearya contain numerous grains in the 480–455 Ma interval (Hadlari et al., 2014; Beranek et al., 2015), which are not abundant in the Middle Permian to Lower Triassic samples analyzed, thus ruling out Pearya as a significant source for these. The 400–350 Ma sub-populations are interpreted to have been sourced from intrusions related to arc magmatism within Crockerland prior to its accretion to the Laurentian margin and to syn- to post-tectonic magmatism related to the Ellesmerian Orogeny, based on the evolved Hf isotopic signature of zircons yielding dates within this age bracket (Anfinson et al., 2012b).

The Middle Permian to Lower Triassic samples from northern Axel Heiberg Island also exhibit a spread of Permian dates between 295 and 250 Ma, a sub-population similar to that previously found in Lower Triassic samples from northern Axel Heiberg Island (Omma et al., 2011). It is important to note that relatively thick Permian to Triassic sandstone samples collected some 300–500 km to the southwest in the Isachsen J-37 (Ellef Ringnes Island) and Brock C-50 (Brock Island) wells (Fig. 1) do not contain Permian zircons, but are instead dominated by the 420–350 Ma sub-population (Anfinson et al., 2016). This population, in addition to the absence of Permian grains, suggests the clastic material in these Permian and Triassic deposits comprise sediments recycled from the Devonian Clastic Wedge (Anfinson et al., 2016). This is turn suggests that the Crockerland watershed that funneled sediments to the area now occupied by northern Axel Heiberg Island during the Middle Permian to Early Triassic was not the same drainage system that brought contemporaneous clastic sediments in the area now occupied by Ellef Ringnes to Brock islands to the southwest.

Three hypotheses have been proposed to address the provenance of 295–250 Ma grains found in Triassic strata of the Sverdrup Basin: (1) Late Paleozoic volcanism within the Sverdrup Basin (Omma et al., 2011; Anfinson et al., 2016); (2) derivation from granitoids on Taimyr Peninsula and the Polar Urals (Omma et al., 2011); and (3) unexposed crust of uncertain nature beneath the Arctic Ocean (submerged areas of Chukotka and the Chukchi Borderlands) (Omma et al., 2011), potentially related to arc magmatism (Midwinter et al., 2016). These three hypotheses are addressed below.

**Late Paleozoic Volcanism within the Sverdrup Basin**

Permian volcanic units are known from the Sverdrup Basin, Alaska’s North Slope, the Uralian Orogen, and the Siberian Traps (Beauchamp, 1995; Cameron and Muecke, 1996; Vernikovsky et al., 1995, 2003; Pease, 2001; Embry and Beauchamp, 2008; Reichow et al., 2009; Omma et al., 2011). In the Sverdrup Basin, Carboniferous and Permian volcanic rocks are alkaline basalts that form relatively thin units of short duration of eruption comprising a small number of individual flows restricted to two small areas. The first area is along the basin’s southern margin, west and south of Borup Fiord Pass on Ellesmere Island. Here a thin unannamed unit of lowest Artinskian (ca. 290 Ma) basalts and volcaniclastic rocks outcrops in the vicinity of Oobloyah Bay (Morriss, 2013). A thicker and more widespread unit of lower Kungurian (ca. 278 Ma) basalts, the Esayoo Volcanics, occurs at Mount Leah and in the Krieger Mountains (Thorsteinsson, 1974). The second area is along the basin’s northern margin from northern Axel Heiberg Island to northwestern Ellesmere Island (Kleybotle Peninsula). Here Lower Carboniferous (upper Serpukhovian; ca. 323 Ma) basalts, the unit named the Audhild volcanics, contemporaneous with the second rifting pulse of the Sverdrup Basin (Embry and Beauchamp, 2008), lie in the upper part of the Borup Fiord Formation (Trettin, 1988; Thorsteinsson, 1974). An unnamed unit of uppermost Carboniferous (Gzhelian) basalts occur within the upper Nansen Formation on northwestern Axel Heiberg Island (Mayr et al., 2002). The Lower Permian Esayoo Volcanics was also mapped in two discrete areas on northern Axel Heiberg Island (Thorsteinsson, 1974; Mayr et al., 2002), but it is likely younger than its southern margin counterpart, as it lies above the unconformity at the top of the Great Bear Cape Formation. It is thus probably late Kungurian (ca. 272 Ma) in age. The geochemical signatures of these basalts point to an intraplate origin for the magma from which they originated that is most likely related to the thinning of the lithosphere, elevated heat flow, partial melting, and possible underplating associated with the rifting processes that led to the Sverdrup Basin following the collapse of the Ellesmerian Orogen (Cameron and Muecke, 1996; Embry and Beauchamp, 2008; Morris, 2013).

These various volcanic units did not provide any zircons to the samples of the same age analyzed in this study, despite having been collected from Pennsylvanian sandstones interfingerling with basalts (SvB-01) and from Lower to Middle Permian shales and sandstones immediately overlying eroded Esayoo basalts at the southern margin (SvB-04 and Svb-05, respectively). Outpouring of this volcanic material was episodic, short-lived and of limited stratigraphic and geographic extent on both northern Axel Heiberg Island and on northwestern Ellesmere Island. In contrast, the spectrum of zircons that is repeatedly found along the northern margin of the basin, while lacking Carboniferous zircons, spans the entire Permian interval (295–250 Ma) and extends into the Early Triassic. This sub-population is abundant, often dominant, in most Middle and Upper Permian and Lower Triassic samples, requiring a high number of zircons to be sourced from these basalts, which is unlikely due to the low zircon productivity of this lithology. The chronological, lithological, and areal constraints of upper Paleozoic volcanic units in the Sverdrup Basin, in addition to the lack of zircons of near-depositional age in samples immediately overlying or interfingerling with these volcanic rocks, suggests a different magmatic source for the 295–250 Ma zircons in Permian and Triassic strata of the Sverdrup Basin.

**Uralian and Siberian Provenance**

A far-traveled Uralian or Siberian provenance for the near-depositional zircons found in Middle Permian, Upper Permian, and Lower Triassic units of the northern Sverdrup Basin, as proposed for Mesozoic strata by Anfinson et al. (2016), is problematic. Transportation of sediments from the Urals into the Sverdrup Basin could only be explained by long distance airborne and/or fluvial transport. Airborne transport can be ruled out based on the abundance, continual stratigraphic range, and limited geographical extent of the 295–250 Ma zircons in the Sverdrup Basin. Far-traveled ash-fall deposits would have blanketed much larger areas extending over both the northern and southern margins of the basin. Such deposits would also be unlikely to be stratigraphically persistent in one small area for more than 40 m.y.

Rivers carrying sediment from the Urals into the Sverdrup Basin, as proposed by Anfinson et al. (2016) require Crockerland to be a large, low-lying landmass to allow for sediment bypass. Such an inferred physiography flies against the strong evidence of pre-Early Triassic uplifts on northern Axel Heiberg Island, most likely extending to the northwest on Crockerland. Accordingly, erosion related to the development of the sub-Changhsingian (sub-late Late Permian) unconformity cuts deeply down-section toward the northwest, eventually removing the entire upper Paleozoic succession, such as west of Aurland Fiord on northwestern Axel Heiberg Island where the Lower Triassic Blind Fiord Formation rests directly on Franklinian basement strata (Fig. 3) (Mayr et al., 2002). Clearly, Crockerland was everything but a low-relief flat land during the Middle and Late Permian. Furthermore, the Uralian fluvial hypothesis requires the existence of ~1000-km-long land bridge linking the northernmost portion of the Uralian Orogen with Crockerland, such as portrayed by Anfinson et al. (2016) for the Late Triassic. Such a bridge is nowhere.
to be seen in any of the large numbers of Middle to Late Permian plate reconstructions found in the literature, including that of Anfinson et al. (2016) for the Middle Permian, for there is simply no evidence that such a paleogeographic feature existed at that time. In contrast, the area between the northern Urals and Crockerland, which is represented by the northern extension of the Barents Sea, was a broad open marine seaway that connected the Paleo-Pacific Ocean to the west with the Barents Shelf, Finnmark Platform and Timan-Pechora Basin to the east (e.g., Anfinson et al., 2016).

Additional evidence against the Uralian fluvial hypothesis includes the fact that a large fluvial system from the Urals would transport sediments sourced from a large drainage area including a large portion of the orogen, as well as eroded foreland basin sediments. The consistent stratigraphically narrow 295–250 Ma zircon sub-population found in samples SvB-07 to SvB-13 contrasts with the abundance of grains yielding dates between 340 and 260 Ma in various Triassic units of Russia and the Barents Sea, interpreted to have received sediments from the Uralian Orogen (Miller et al., 2006; Sololiev et al., 2015; Ershova et al., 2015a; Zhang et al., 2016; Klausen et al., 2017; Ershova et al., 2017). The far-traveled, fluvial transport interpretation is thus at odds with the 340–295 Ma gap in the detrital zircon spectra of Middle Permian to Lower Triassic strata of the northern margin of the Sverdrup Basin. This implies that the drainage areas for these sediments did not incorporate zircon-bearing rocks or sediments containing these of age interval for ~40 m.y. These strata are lithologically heterogeneous, ranging from pebble-sized chert conglomerate to fine-grained sandstone, which, added to the euhedral, relatively unabraded morphology of the 295–250 Ma grains found by Omma et al. (2011) in lowermost Triassic strata on the northern margin of the Sverdrup Basin, imply minimal transport.

Additionally, Upper Triassic strata of the Sverdrup Basin contain zircons as young as ca. 210 Ma (Anfinson et al., 2016; Midwinter et al., 2016). The youngest igneous bodies documented in the Urals are syenite-granitic stocks (249–241 Ma) and mafic intrusions (229–227 Ma) related to magmatism associated with the Siberian Traps (Vernikovsky et al., 2003; Walderhaug et al., 2005), and are thus not a plausible source for the near-depositional zircons in Upper Triassic units of the Sverdrup Basin.

Unexposed Crust beneath the Arctic Ocean

The remaining explanation for the source of 295–250 Ma zircons in Middle Permian to Lower Triassic strata requires magmatic activity occurring north of the Sverdrup Basin spanning the Permian and Early Triassic. Continuous influx of near-depositional zircons into the northern part of the basin for over 40 m.y. requires long-lasting, proximal, localized magmatic activity in a landmass located outboards of the northern portion of the Sverdrup Basin. That landmass (Crockerland) became emergent by the Roadian (early Middle Permian), coinciding with the first major clastic influx from the north. The accompanying Paleozoic and Precambrian zircon sub-populations present in the samples derived from this landmass point at the existence of evolved crust containing Timanian, Caledonian, and Ellesmerian aged basement or sedimentary cover, as well as Precambrian rocks and sediments with age distributions similar to the Permian samples on the southern margin and the upper Pennsylvanian to Lower Permian samples of the northern margin. Magmatism in this landmass began in the earliest Permian (ca. 300 Ma), coincident with the change in stress fields in the Sverdrup Basin that caused a transition from post-rift passive subsidence to episodic basin inversion (Beauchamp et al., 2001; Embry and Beauchamp, 2008). The tectonic setting that best explains the detrital zircon data set and the stratigraphic, sedimentological, and structural observations is that of a convergent margin in which a magmatic arc developed as a response to the initiation of a subduction zone ca. 305–300 Ma. Considering the detrital zircon signature of Middle Permian to Lower Triassic strata of the northern margin of the Sverdrup Basin, which is dominated by near-depositional dates, the existence of a Permian-Triassic magmatic arc is consistent with the characteristic signature of sediments deposited in the convergent margin setting signature as compiled by Cawood et al. (2012).

Previous work by Embry and Anfinson (2013) also referred to the presence of near-depositional zircons in Upper Triassic strata of the Sverdrup Basin and proposed the existence of magmatic activity in Crockerland related to the paleo-Pacific margin. Furthermore, HF isotopic measurements carried out on 350–210 Ma zircons from Upper Triassic units in northern Axel Heiberg Island display a broad range of values without any noticeable differentiation trends, suggesting derivation from a mixture of evolved, intermediate and juvenile lithosphere, interpreted as a continental arc signature (Midwinter et al., 2016). These data, combined with the presence of near-depositional zircons and newly described bentonites in Triassic strata of the Sverdrup Basin, are consistent with a convergent margin setting along the northwestern edge of Laurentia (Midwinter et al., 2016; Hadlari et al., 2017). The detrital zircon signatures of Upper Triassic and younger strata of the Sverdrup Basin contain grains yielding a spread of dates between 230 and 210 Ma (Anfinson et al., 2016; Midwinter et al., 2016), contrasting with the isolated 295–250 Ma sub-population found in Middle Permian to Lower Triassic strata of the Sverdrup Basin. Therefore, the source of near-depositional grains in Middle Permian to Lower Triassic units must differ from the sources of detrital zircons in Upper Triassic and younger strata.

Relevant to this discussion is the fact that Triassic strata in the Barents Sea contain a young near-depositional 250–210 Ma sub-population, interpreted by Klausen et al. (2017) as derived from inferred magmatic activity associated with the development of the Novaya Zemlya fold and thrust belt. Cobbles yielding Permian dates are also present in Jurassic strata of Franz Josef Land, derived from basement uplifts containing plutonic rocks of this age, although it is unclear where they were derived from and the mechanisms responsible for this magmatism (Ershova et al., 2017). Triassic strata in Chukotka and the Lisburne Hills in Alaska also contain a young, near-depositional zircon sub-population of uncertain origin yielding Carboniferous to Triassic dates (Miller et al., 2006; Tuchkova et al., 2011). Miller et al. (2006) and Tuchkova et al. (2011) suggested a Uralian and Siberian provenance for these zircons in Chukotka and the Lisburne Hills, although Tuchkova et al. (2011) noted that the Late Triassic shelf depositional environment of the Lisburne Hills was incompatible with a Uralian or Siberian source. Thus, the possibility of two or more unidentified sources of Permian to Triassic zircons in the Arctic region, and their implications for paleogeographic reconstructions cannot be discarded.

Evidence for the Magmatic Arc

Zircon grains yielding Permian and earliest Triassic dates in Middle Permian to Lower Triassic strata of the northern margin of the Sverdrup Basin, accompanied by the evidence of local derivation of these rocks, calls for the existence of a magmatic arc located north of the Sverdrup Basin during the Permian to Triassic (Fig. 9). This magmatic arc would comprise Timanian-aged crust involved in the Ellesmerian Orogeny and minor abundance of Caledonian-aged rocks. It would have experienced continuous magmatism throughout the Permian distinct from the magmatism that shed young zircons onto the Siberian margin and Chukotka.

Development of this hypothetical magmatic arc to the north of the Sverdrup Basin would have followed the initiation of a southeast-dipping subduction zone ca. 305 Ma and would have remained magmatically active from the earliest Permian (ca. 300 Ma) to at least the earliest Triassic (ca.
Implications for Arctic Paleogeography

Understanding the role of this magmatic arc in relation to all other tectonic elements in the Arctic realm is crucial for reconstructing its paleogeography during the late Paleozoic and early Mesozoic. Beginning in the Late Devonian, the crustal block on which Permian arc magmatism took place (namely Crockerland), was located within the Arctic Alaska–Chukotka Microplate and was involved in the Ellesmerian Orogeny, as indicated by Ellesmerian-aged zircons (390–355 Ma) derived from this landmass and its inferred paleogeographic position (Embry, 1993; Miller et al., 2006; Beranek et al., 2010).

Detrital zircon and stratigraphic evidence from Chukotka, Wrangel Island, and the Kara Block (Severnaya Zemlya and northern Taimyr) place these elements adjacent to the Laurentian and Baltic margin, respectively, during the Devonian (Kos’ko et al., 1993; Miller et al., 2010; Ershova et al., 2015a, 2015b, 2015c, 2016; Pease et al., 2015). Between the Devonian and Carboniferous, the Kara Block detached from the Baltic-Laurentia margin and collided against the Siberian margin, as interpreted from a change in sediment provenance from Baltic to Uralian sources between these periods (Pease et al. 2015; Ershova et al., 2015a). As such, post-collisional rifting associated with the initiation of subsidence in the Sverdrup Basin may have had a northeastern continuation through which the Kara Block rifted apart and became disconnected from the Baltic margin (Ershova et al., 2016). The northern edge of the Sverdrup Basin was dominated by carbonate platform sedimentation during much of the Pennsylvanian and Early Permian, with little to no clastic detritus derived from northern sources due to the paucity of emergent land to the north of the basin (Beauchamp, 2015). Most current models of Arctic tectonic evolution place Crockerland adjacent to the Sverdrup Basin up until the opening of the Amerasia Basin by the Cretaceous (Fig. 10), with fragments of Crockerland now included in the Chukchi Borderlands based on its position after restoration of the opening of the Arctic Ocean. (Miller et al., 2006; Lawver et al., 2011; Lavrov et al., 2013; Gottlieb et al., 2014; Amato et al., 2015; Hadlari et al., 2016; O’Brien et al., 2016).

The convergent margin required to explain the detrital zircon signature of Middle Permian to Lower Triassic strata from the northern margin of the Sverdrup Basin conflicts with most reconstructions of the Arctic Alaska–Chukotka Microplate, which consider the Pacific side of this entity as a passive margin (e.g., Miller et al., 2006, 2010; Lavrov et al., 2013; Anfinson et al., 2016). However, Midwinter et al. (2016) challenged the passive margin hypothesis based on the predominance of Carboniferous to near-depositional zircons in Upper Triassic strata from the Sverdrup Basin with HF isotopic signatures of a continental arc (Midwinter et al., 2016), as well as the presence of similar near-depositional zircons in Triassic units in the Lisburne Hills, Chukotka, and Wrangel Island (Miller et al., 2006, 2010; Tuchkova et al., 2011; Amato et al., 2015), too young to be sourced from any known magmatic rocks in the Urals and Siberia. Permian to Triassic northerly derived strata in Chukotka incorporate near-depositional zircons, volcaniclastic debris (tuffs, lapilli and volcanic lithic fragments) and geochemical characteristics (Th/U ratio and Nd isotopic signatures) that point at a contribution from juvenile, undifferentiated arc sources (Tuchkova et al., 2011), questioning the passive interpretation for this margin.

A convergent margin setting for Chukotka in the late Paleozoic to Mesozoic is compatible with geological observations, given that large-scale correlations are hampered by overprinting due to Mesozoic orogenesis, and that the lack of documentation of a Permo-Triassic subduction complex can be explained by poor preservation due to underplating beneath the arcs accreted in the Jurassic (see Amato et al., 2015, and references therein), and the remoteness and lack of detailed mapping of this region. No evidence of a late Paleozoic to early Mesozoic active margin, or Permo-Triassic magmatic activity (except for the volcanics encountered in the Tunilik-1 well in the Chukchi Sea; Beauchamp, 1995), has been documented within Arctic Alaska, probably due to similar reasons. There

![Figure 9. Comparison of the probability density plots of Middle Permian to Lower Triassic strata of the southern margin of the basin analyzed in this study with other data sets. n—number of accepted analyses; s—number of samples.](https://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/10/3/426/4180110/426.pdf)
exists, however, a record of an active margin farther south in the Yukon during Permian to Triassic time and the opening of an oceanic backarc basin, the Slide Mountain and Angayucham oceans (see Colpron and Nelson, 2011, and references therein). Thus, an active margin setting for the paleo-Pacific margin of Arctic Alaska–Chukotka should be considered, even preferred, when explaining the tectonic setting of the Sverdrup Basin and adjacent domains during the late Paleozoic and early Mesozoic.

A more complex reconstruction than a single subduction zone is required due to the discrepancies in the detrital zircon spectra between Lower Triassic strata in Chukotka–Wrangel Island and the Sverdrup Basin, which represent two distinct sources of near-depositional zircons. Such separation into two different magmatic domains arises from the prolonged and reproducible absence of 340–300 Ma zircons in Permian and Lower Triassic strata of the Sverdrup Basin. Zircons yielding dates within the 340–300 Ma interval did not appear in the Sverdrup Basin until the Norian (Late Triassic) (Anfinson et al., 2016; Midwinter et al., 2016), that is ~50 m.y. after northerly derived sedimentation in the Sverdrup Basin began. An alternative model with a single arc would require a landward migration of arc magmatism and the drainage divide, which would prevent grains aged 340–300 Ma from reaching the Sverdrup Basin, even from recycling of older strata. Such an explanation requires shallowing of the subduction angle and/or an underplating event causing partial melting of the crust in which the arc developed, as well as a spatially restricted catchment area for the basin for over 40 m.y., and is therefore deemed unlikely. Furthermore, the detrital zircons analyzed yielding Permian and Early Triassic dates do not show evidence of inherited cores, a characteristic that would be expected from zircons sourced from magmas originated through partial melting of the crust due to underplating.

The following speculative model for the tectonic evolution of the Sverdrup Basin (Figs. 10 and 11), which integrates the available geochronological data and geological observations from the regions involved, begins with the development of a backarc basin between Chukotka–Wrangel Island and the Laurentian margin immediately following the collapse of the Ellesmerian Orogen in the early Mississippian.

This backarc basin represents a northern extension of the chain of backarc basins developed along the northwestern margin of Laurentia (Slide Mountain and Angayucham oceans) documented by Colpron and Nelson (2011) and Israel et al. (2014). The rapid collapse of this orogen can be explained in this model by a shift in the stress regime from compression to extensional due to subduction initiation and slab-rollback of the convergent margin beneath Arctic Alaska–Chukotka. This newly created extensional regime in a backarc position could have induced the initiation of Sverdrup Basin subsidence, creating depocenters within the Laurentian margin and the terranes now incorporated within the Arctic Alaska–Chukotka Microplate, as indicated by the distinct geochronological signature of older Paleozoic zircons in various areas considered to be part of this landmass (Miller et al., 2010; Ershova et al., 2015c, 2016). Analogues of this proposed backarc-induced collapse of the Ellesmerian Orogen are also recognized along the Variscan Orogen, which led Ziegler (1988) to first propose that this mechanism was responsible for the onset of subsidence in the Sverdrup Basin.

The isolated 295–250 Ma zircon sub-population is interpreted in our model to have originated from a magmatic arc that started developing in the latest Carboniferous to earliest Permian outboard of the Sverdrup Basin, in the hypothetical terrane that Embry (1993) termed Crockerland. By the Middle Permian, a change in subduction dynamics underneath Crockerland led to the emergence of the magmatic arc and onset of siliciclastic sedimentation along the northern margin of the basin, providing a source of Permian zircons. Upper Triassic to Lower Jurassic strata of the Sverdrup Basin contain 340–300 Ma and younger sub-populations, yielding nearly identical detrital zircon signatures to Triassic strata of Chukotka and Wrangel Island (Miller et al., 2010; Tuchkova et al., 2011; Omma et al., 2011; Anfinson et al., 2016; Midwinter et al., 2016), implying that the magmatic arc that sourced Triassic strata of Wrangel Island and Chukotka became a source of sediment for the Sverdrup Basin by the Late Triassic (Midwinter et al., 2016; Hadlari et al., 2017). This is proposed here to have occurred after closure of the backarc basin that formed during the Carboniferous between the Laurentian margin and Chukotka, and subsequent amalgamation of both magmatic arcs in the latest Permian to Early Triassic. Accretion of these land masses to the northern margin of the Sverdrup Basin is proposed as the mechanism for the development of the sub-Changhsingian (sub-late Late Permian)
unconformity and the deepening of the basin in the earliest Triassic, as well as the major influx of northerly derived sediments in the Late Triassic (Heiberg Formation) as the product of the erosion of the highlands to the north, with the accompanying shift towards a juvenile Nd isotopic signature (Patchett et al., 2004; Embry and Beauchamp, 2008; Embry, 2009). However, none of the Permian and Lower Triassic samples that Patchett et al. (2004) analyzed for Nd isotopes were collected from northerly derived units, and thus it is likely that this juvenile shift occurred during the Middle Permian in the northern margin of the basin. The proposed opening and closure of the backarc basin and the juxtaposition of the two arcs with the Laurentian margin, is similar in time and configuration to the evolution of the Yukon-Tanana terrane and the Slide Mountain Ocean farther south, which closure culminated in the Late Permian Klondike Orogeny (Beranek and Mortensen, 2011; Colpron and Nelson, 2011; Israel et al., 2014).

The initiation of a subduction zone beneath Crockerland may have occurred in response to the changes in plate rotation of Euramerica (Laurussia) after its collision with the Kazakhstan plate near the Carboniferous–Permian boundary (Nikishin et al., 1996; Torsvik et al., 2001). Lower to Middle Triassic units in Svalbard do not contain Permian to Triassic zircons (Bue and Andresen, 2014), and in the absence of detrital zircon studies of Permian to Triassic units in northern Greenland, the easternmost extent of this subduction zone is placed offshore of Ellesmere Island in the Canadian Arctic Archipelago. Permian to Triassic strata in the subsurface near Ellesmerian Orogen and further south do not contain the 295–250 Ma detrital zircon sub-population (Anfinson et al., 2016), which, added to the absence of volcanic deposits and post-Early Permian deformation in the western portion of the basin, limits the western extent of the proposed subduction zone to offshore of Ellesmerian Orogen (Fig. 10).

Subduction initiation and accretion of pericratonic terranes along the margins of Pangea have been proposed to occur in response to a large scale change in the stress regime after closure of the Uralian Trough and culmination of the Uralian Orogen in Late Permian to earliest Triassic time (Cawood and Buchan, 2007). It is worth considering that the main hypothesized subduction zone beneath Arctic Alaska–Chukotka represents the northern continuation of the convergent margin in which the Uralian Orogen developed, with more complexities than we are able to elucidate, potentially incorporating elements similar to the tectonic configuration of the present-day southwestern Pacific. If this was the case in the Canadian Arctic, Late Permian deformation events in the Sverdrup Basin could be linked to resulting changes in the subduction dynamics of these magmatic arcs and their backarc regions, although the specific operating mechanisms remain a matter of debate.

CONCLUSIONS

Using detrital zircon U-Pb geochronology of upper Paleozoic to Lower Triassic strata of the Sverdrup Basin three main sediment sources are recognized. Lower Permian sediments on the southern and northern margins were derived from erosion of adjacent highlands resulting from episodes of basin inversion, with no zircons derived from the volcanic units in the area (Esayoo Formation and Carboniferous-Permian volcanics). After peneplanation of the pre-Roadian relief, Middle Permian sediments in the Sverdrup Basin were derived from sources in the Canadian and Greenland shields, with some reworking of grains from underlying units.

Middle Permian to lowermost Triassic successions along the northern margin of the Sverdrup Basin contain detrital zircons of Permian to...
earliest Triassic age (295–250 Ma) forming a sub-population isolated from other Paleozoic sub-populations, interpreted to derive from a newly defined magmatic arc that experienced magmatism throughout this time interval and different from any other magmatic events within the Arctic region recognized to this date. This convergent system originated in the backarc region of a convergent margin near Chukotka and Wrangel Island, resulting in a second subduction zone underneath Crockerland beginning near the Carboniferous–Permian boundary, with a southeasterward dip and located adjacent to the northeastern portion of the Sverdrup Basin. Continued subduction led to the closure of the backarc basin and the amalgamation of the two magmatic arcs against the margin of Laurentia, affecting the Sverdrup Basin evolution during the late Paleozoic to early Mesozoic.

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